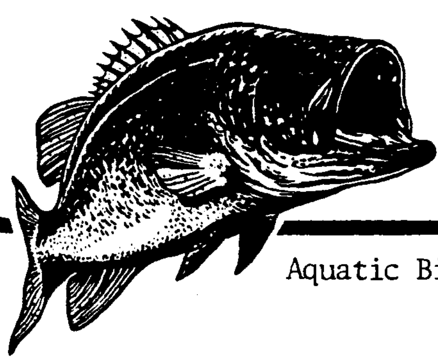
ILLINOIS NATURAL HISTORY SURVEY

BIOLOGICAL CONTROL OF AQUATIC MACROPHYTES BY HERBIVOROUS CARP

Part 1. EXECUTIVE SUMMARY

Aquatic Biology Section Technical Report

M. J. Wiley and R. W. Gorden
Principal Investigators



Final Report
Federal Aid Project F-37-R

Aquatic Biology Technical Report 1984(10)

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BIOLOGICAL CONTROL OF AQUATIC MACROPHYTES BY HERBIVOROUS CARP

Part I. Executive Summary

Final Report, Federal Aid Project F-37-R

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GUIDE TO CHAPTERS BY D-J JOB DESIGNATION

In order to facilitate the identification of report contents with federal study and job classifications used in the AFA for F-37-R, the following guide is presented. In addition to listing chapters in this final report, references to appropriate publications supported by this contract are also given.

STUDY 101: A comparison of the effects of hybrid grass carp and selected aquatic herbicides on aquatic vegetation and the sport fishery.

Job 101.1. Determination of existing aquatic macrophytes--Part 2: Chapter 5.

Job 101.2. Control--Part 2: Chapters 2 and 3; Gorden et al. 1982

Job 101.3. Water quality--Part 2: Chapter 3

Job 101.4. Establish of fish populations--Part 2: Chapter 3

Job 101.5. To determine growth characteristics--Part 2: Chapters 1, 2, and 3.

Job 101.6. Reproduction--Part 2: Chapters 4 and 5

STUDY 102. The effects of the control of aquatic vegetation by hybrid grass carp and by herbicides on the rates of decomposition, nutrient cycling and flow and the subsequent effect on the bass, bluegill, and catfish populations.

Job 102.1. Measurement of invertebrate and microbial populations--Part 2: Chapter 3

Job 102.2. Rates of deocmposition of aquatic macrophytes--Part 2; Chapter 3; Gorden et al. 1982

Job 102.3. Nutrient cycling studies--Part 2: Chapter 3

Job 102.4. Energy flow--Part 2: Chapter 1

Job 102.5. Systems analysis--Part 3; Wiley et al. 1983

STUDY 103: Genetic composition and reproductive capability of F1 hybrid carp.

Job 103.1. Genetic composition and uniformity--Executive summary; Magee and Philipp 1982

Job 103.2. Gonadal development--Part 2: Chapter 5

Job 103.3. Reproductive capability--Part 2: Chapter 4

Part 1

EXECUTIVE SUMMARY

INTRODUCTION

Nuisance aquatic plant control has become a multi-million dollar problem in Illinois[1]. Naturally occurring plant populations, often fueled by increasing rates of cultural eutrophication, regularly interfere with fishing, swimming, boating, and other recreational pursuits on which people place considerable social and economic value. In addition to hindering recreational uses of surface waters, excessive plant growth can impede flow in industrial cooling and distribution systems and in agricultural irrigation systems, and can reduce the capacity of reservoirs used for municipal water supplies. Given this potential for interference with human activities, the public's desire for an effective and inexpensive method of plant control is easily understood.

Presently there are three basic technologies available for the removal of aquatic vegetation: (1) mechanical, (2) chemical, and (3) biological. In Illinois, only the first two are generally available to the public and both have serious drawbacks. Mechanical removal by harvesting devices is extremely costly and provides only short-term control. Furthermore, because it is costly and labor intensive, its large-scale use on sizable bodies of water becomes a practical impossibility. Chemical control requires much less labor and can be used in even the largest lakes and reservoirs. However, its high cost (typically $100-400 per hectare treated, excluding application costs) and often acute ecological effects on nontarget species limit the desirability of the widespread use of chemicals.

[1] Surprisingly, no government or private body in Illinois keeps records on the amount of aquatic herbicide sold or applied within the state. Last year, the Fisheries Division of the Illinois Department of Conservation (DOC) spent approximately $30,000 on herbicides managing aquatic plant growth on 9,000 acres of state and public waters. Using the ratio of herbicide costs per acre management ($7/acre) for those lakes treated by the DOC, we can roughly estimate that $1.5 million was spent on herbicides statewide last year alone. This estimate, of course, is only for herbicide applications. Mechanical harvesting, consulting, etc., would likely push the total cost well over $2 million per year.

Biological control of aquatic vegetation has been feasible for some time (Aliev 1963, Nikolsky and Aliev 1974, Bailey 1978) using several herbivorous fishes not naturally occurring in the United States; the most prominent are the white amur (Ctenopharyngodon idella) and several species of Tilapia (Shireman 1984). Since tilapia are not cold-hardy, they are of little use in the Midwest; but the grass carp (also known as the white amur) has been used extensively for plant control in several Midwestern states (e.g., Arkansas, Missouri, Iowa, Kansas) since the late 1970's (Shireman and Smith 1983). The problem with the white amur has been that its enormous feeding and growth capacity make it a potential pest of catastrophic proportions, if large-scale natural reproduction were to occur in major drainage systems, such as the Mississippi and Illinois rivers. Fear of such an eventuality, coupled with recent negative experiences with the introduction of other exotic species, has led most states, including Illinois, to outlaw the importation and use of the white amur for all but scientific purposes.

The potential for ecological damage is real (see Summary of Results) and, in our view, cannot be ignored, even though the probability of large-scale reproductive success in the next decade or so is negligible. Given even a small amount of successful recruitment, natural selection, operating over the long term, will result in a slow but sure adaptation of the stock, increasing the likelihood of major reproductive success. Natural reproduction of escaped grass carp has already been reported in several U.S. rivers, including the Mississippi (Conner et al. 1980; R. Nobel, personal communication), although recruitment to larger size classes is undocumented. The continuous escapement of fish, both legally and illegally stocked, provides an ongoing population of adults for natural experiments in reproduction. Large-scale escapement from stocking (primarily in Missouri) over the last 10 years has resulted in "feral" populations throughout most of the Mississippi River drainage and even in the lower reaches of the Illinois River. Additional white amur have been brought into Illinois waters illegally by private citizens for plant control. As a result, the number of white amur already in Illinois waters is surprisingly high. In 1981, close to 10,000 lbs were taken by Illinois commercial fishermen, and in recent years grass carp catches have been about 0.5-1.0% of the state's common carp catch (S. Jackson personal communication, B. Fritz personal communication).

Planning for the research program described in this report began in late 1979, at a time when the tension between fears of environmental damage and desires for an inexpensive biological control agent appeared to be resolved. Hungarian researchers had reported the development of a hybrid cross between the white amur and another Chinese carp, the bighead carp (Hypophthalmichthys nobilis); the hybrid was purported to be both herbivorous and sterile (Bakos et al. 1978). By 1979, commercial producers in Arkansas (J. M. Malone & Son Enterprises) developed mass-production techniques and actively promoted the fish as a sterile equivalent of the white amur. The original scope of this project was to assess the utility of this new hybrid carp for plant control in Illinois and to contrast its potential with prevailing chemical control techniques. During the past 4 years, a series of new genetic developments forced us continuously to refocus our studies, at the same time moving us closer to the goal of obtaining an ecologically "safe" biological control agent.

When we began work in 1980, the triploid hybrid was the only available potential substitute for the white amur. In spring 1981, after a year of preliminary studies, the first batch of hybrids was received for field trials. These fish, provided by J. M. Malone & Son Enterprises, had been produced in 1980. In late 1981 after an extensive electrophoretic examination of both our fish and of random samples from the producer's rearing ponds, Dr. Philipp of our group discovered that a large proportion of the fish produced in 1980 were not triploid but diploid hybrids (Magee and Philipp 1982). Fortunately, most of our stocked ponds contained fish predominantly of one type or the other (Gorden et al. 1982), but these ploidy differences complicated the situation.

The situation grew even more complex in late 1982 when J. M. Malone & Son Enterprises announced that they used a new technique in summer 1981 that consistently produced triploid hybrids; these new hybrids were referred to as "super-triploids," a designation that acknowledged the generally poor performance of the 1980 hybrids in field trials and laboratory studies across the country (Cassani et al. 1982; Gorden et al. 1982; Osborne 1982; Beaty et al. 1983, Shireman et al. 1983; Wiley et al. 1983).

By the beginning of the 1982 field season, three distinct types of hybrid were in hand, each with potentially different growth and feeding characteristics (Table 1). Growth data for the "super-triploids" in our ponds during summer 1982 indicated that there was, contrary to the producer's claim, no statistically significant difference between the field performance of the 1980 and 1981 triploid hybrids. However, the 1981 batch of fish was 100% triploid and the new production technique did represent an important improvement of those used earlier. With some resolution of the ploidy problem, we began laboratory studies in fall 1982 to: (1) document the energetic basis for differential field performances between the triploid hybrid and the white amur, and (2) provide the basic bioenergetic data necessary to predict growth and consumption in the various climatic regions of Illinois.

In spring 1983, a final and somewhat spectacular development occurred that substantially affected the focus of the final year of our study--the development of production technologies for a triploid white amur. Although the triploid grass carp had been produced experimentally (Stanley 1979) using various induction techniques, the percentage of triploids produced was considered to be too low to make commercial production feasible. Malone's new technique made production of large numbers of triploids possible, and coupled with automated or manual testing, promised large-scale production of 100% triploid white amur. The triploid grass carp appeared to be more likely to retain the voracious appetite of the normal diploid fish, while like the hybrid it probably was incapable of natural reproduction because of its triploid genetic constitution (Part 2: Chapter 4). In fall and winter 1983, we received several shipments of the new triploid fish. These fish were immediately subjected to a series of bioenergetic analyses in the laboratory to compare their potential

Table 1. Genetic composition of herbivorous carp used in field and laboratory experiments.

Year produced	Type	Sampling	Number sampled	Genetic types (%) 3N F1	2N F1	2N GYN	2N	3N
1979	hybrid	hatchery selected, fall 1979	100	100.0	-	-	-	-
1980	hybrid	randomly selected, fall 1980	53	45.3	54.2	-	-	-
		hatchery selected, fall 1980	65	6.2	93.8	-	-	-
		hatchery selected, spring 1981	25	96.0	4.0	-	-	-
1981	hybrid	randomly selected, fall 1981	80	100.0	-	-	-	-
	Gyn-hybrid	hatchery selected, fall 1981*	5	-	-	100.0	-	-
1982	hybrid	randomly selected, fall 1982	100	98.0	2.0	-	-	-
1983	triploid grass carp	hatchery selected, fall 1983	60	-	-	-	-	100.0

*Selected by hatchery personnel as gynogenetic fish.

performance as a control agent with both the normal diploid grass carp and with triploid hybrids.

Because of these new developments since the original AFA in 1980, the scope of our investigations broadened. We examined the biology and ecology of herbivorous carp in general, rather than just those of triploid hybrids, attempting to provide the Illinois Department of Conservation with the data necessary to make the best decision regarding the future legal status of the grass carp and its genetic derivatives in Illinois. To that end, we have attempted to answer four basic questions relating to the potential use of herbivorous carp in this state:

1. How do the triploid hybrid, the triploid grass carp, and the diploid grass carp compare in terms of potential performance as biological control agents?

2. How will the use of herbivorous carp as control agents affect other components of lentic ecosystems, particularly those components related to sport fish productivity and/or yields?

3. What is the reproductive potential of the two possible substitutes for the diploid white amur?

4. What stocking strategies should be used to achieve efficient and effective aquatic plant control?

Detailing the answers to these question comprises the bulk of our final report. In the remainder of this executive summary (Part 1), an overview of project results is presented, along with formal recommendations to the Illinois Department of Conservation regarding the status of herbivorous carp. In Part 2, descriptions of all major studies are given in a chapter format with appendices containing pertinent statistical tables. In Part 3, stocking recommendations are made and a detailed description of their derivation is provided. To facilitate comprehension, the entire report is organized topically rather than by federal job designation. A guide to the report by job number is provided for those interested in relating results to the original and revised (1982) AFA's.

SUMMARY OF PROJECT RESULTS

Bioenergetic Studies

Bioenergetic analyses provided the simplest and most straightforward basis for examining differences between the three types of herbivorous carp and their potential value as biological control agents. Feeding and growth rates together determine the amount of plant removal that can occur in a given length of time. Since both rates are functions of fish size, temperature, oxygen concentration, and food availability and type, they change as a fish grows, as the environment goes through its seasonal cycles, and with more or less stochastic weather-driven changes in the physiochemical-biological structure of experimental ponds. Measuring these rates in a controlled laboratory environment provides indices of performance unaffected by confounding influences. Furthermore, since both rates can be related by the balanced energy equation:

$$C = G + M + aC$$

where C is consumption, G is growth, M is metabolic demand (standard + active), and a is the proportion of consumption not assimilated. An analysis of consumption, growth, and metabolic demand can also provide the basis for a quantitative projection of feeding capacity integrated over time. Such projections are used to generate stocking recommendations presented in Part 3 of this report.

Beginning in the third year of this project, considerable effort went into laboratory studies of consumption, growth, and standard (basal) metabolism. Twenty-one feeding experiments involving triploid hybrids and triploid and diploid grass carp were conducted over 2 years. In addition, the standard metabolism of 115 individual fish was measured in flow-through respirometers. These studies indicated that neither the triploid hybrid nor the triploid grass carp feeds or grows as well as the diploid grass carp (Table 2). However, the triploid grass carp was a close second to the

Table 2. Analysis of covariance for diploid-hybrid regressions of consumption on temperature.

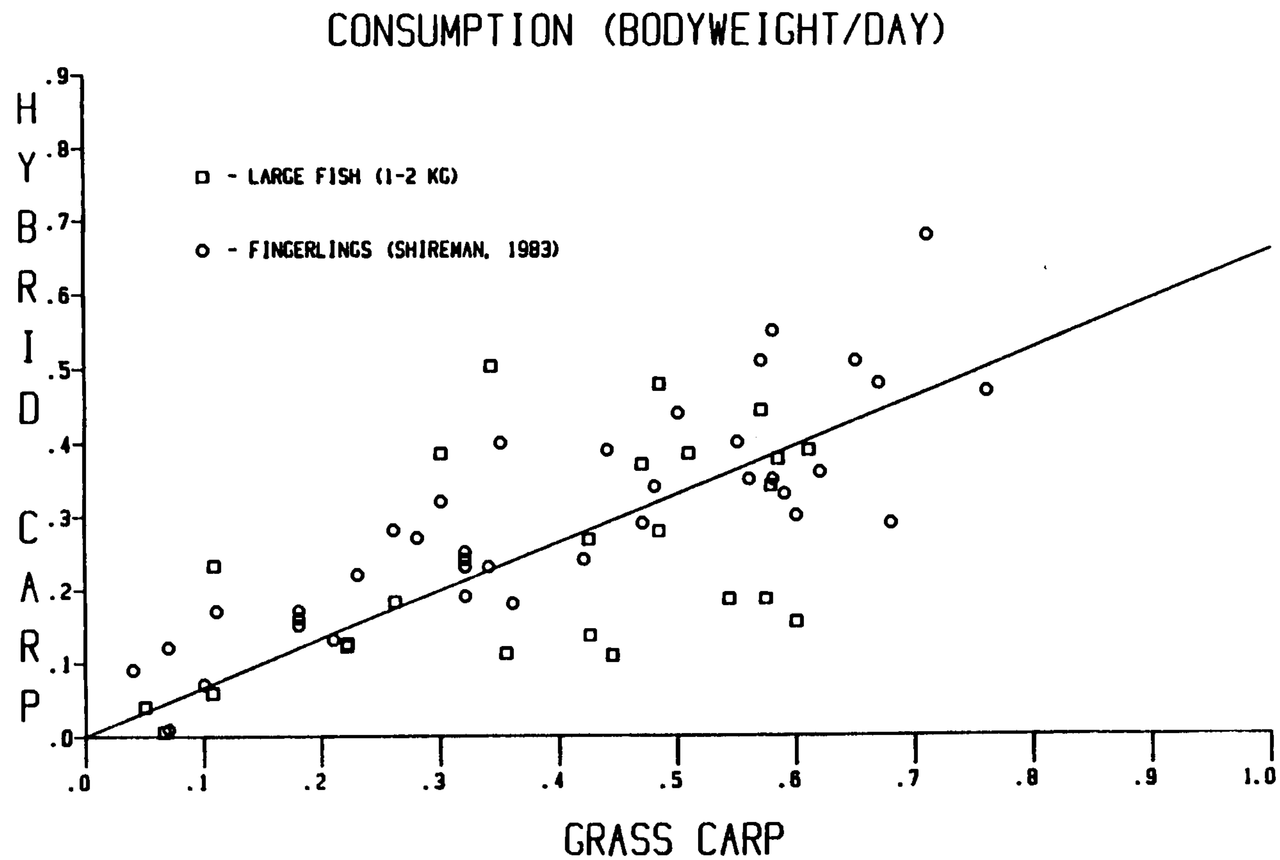
	Analysis of Covariance		
Group	d. f.	SS	MS
Hybrid	93	0.9394	0.01010
Diploid	21	0.3077	0.01465
F = 1.45			
Pooled regression			
	114	1.2471	0.01094
	117	2.0483	0.01770
Difference	3	-0.8012	0.2570
F (3,114) = 24.4			

diploid while the hybrid's performance was substantially poorer than that of either grass carp.

More specifically, consumption rates of the triploid grass carp were consistently about 90% that of the diploid for fish of similar size, feeding on identical food, and at the same temperature (Fig. 1). Hybrid consumption, on the other hand, ran about 66% that of the diploid in paired comparisons (Fig. 2). No statistically significant differences in metabolic rate or assimilation efficiency (U^{-1}) were found between the triploid and diploid grass carp. The hybrids, however, had a significantly different metabolism, particularly at larger body sizes (Fig. 3). For example, a 1-kg hybrid at 25°C had a standard metabolic rate about 4.5% higher than that of an equivalently sized triploid or diploid grass carp; however, a 10-kg hybrid's metabolic rate was 55% higher. This high metabolic demand coupled with a low rate of food consumption results in the poor growth performance of the hybrids. The proportional increase in metabolic costs in larger individuals and a proportional decline in consumption leads to a lower maximum weight in the hybrid, probably not more than several kilograms. Because of slightly reduced consumption rates, the triploid grass carp can be expected to grow more slowly than the diploid, although in feeding experiments this reduction was never more than about 10%.

The effect of temperature on consumption rates also varied between the different types of carp. Although in all cases the temperature response was asymptotic, significant differences in slopes were found both between the hybrid and the diploid grass carp and between the triploid and diploid grass carp (Fig. 4, Table 3). Again, the diploid grass carp appeared to have the most desirable characteristics of the three. Based on our analyses, the lower threshold at which all feeding stops is 10 C for the diploid grass carp, 11 C for the triploid grass carp and, 13 C for the hybrid.

Fig. 1. Grass carp versus hybrid carp consumption (percent body weight/day). Paired data from our experiments for large fish (1-2 kg) and from Shireman (1983).



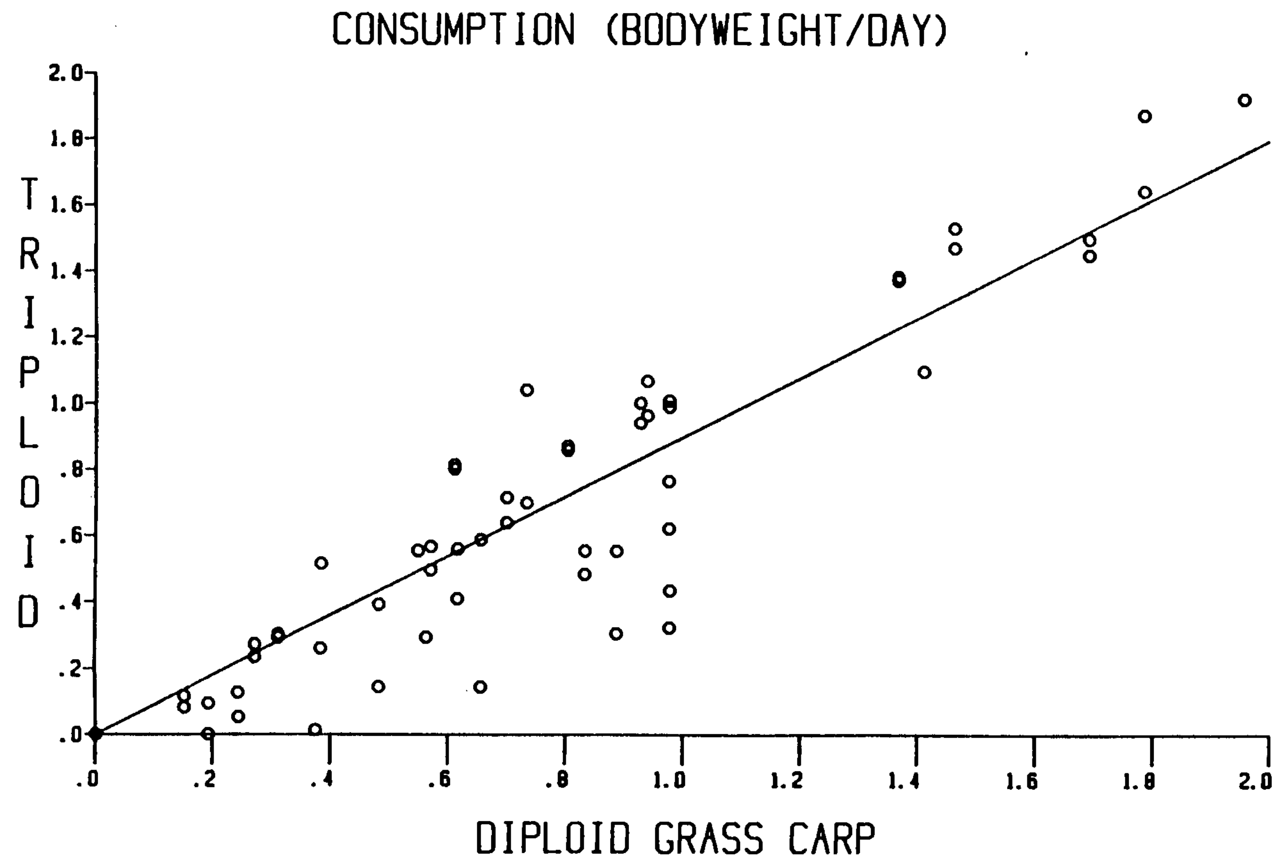


Fig. 2. Triploid versus diploid grass carp consumption (percent body weight/day). Paired data from INHS laboratory feeding studies.

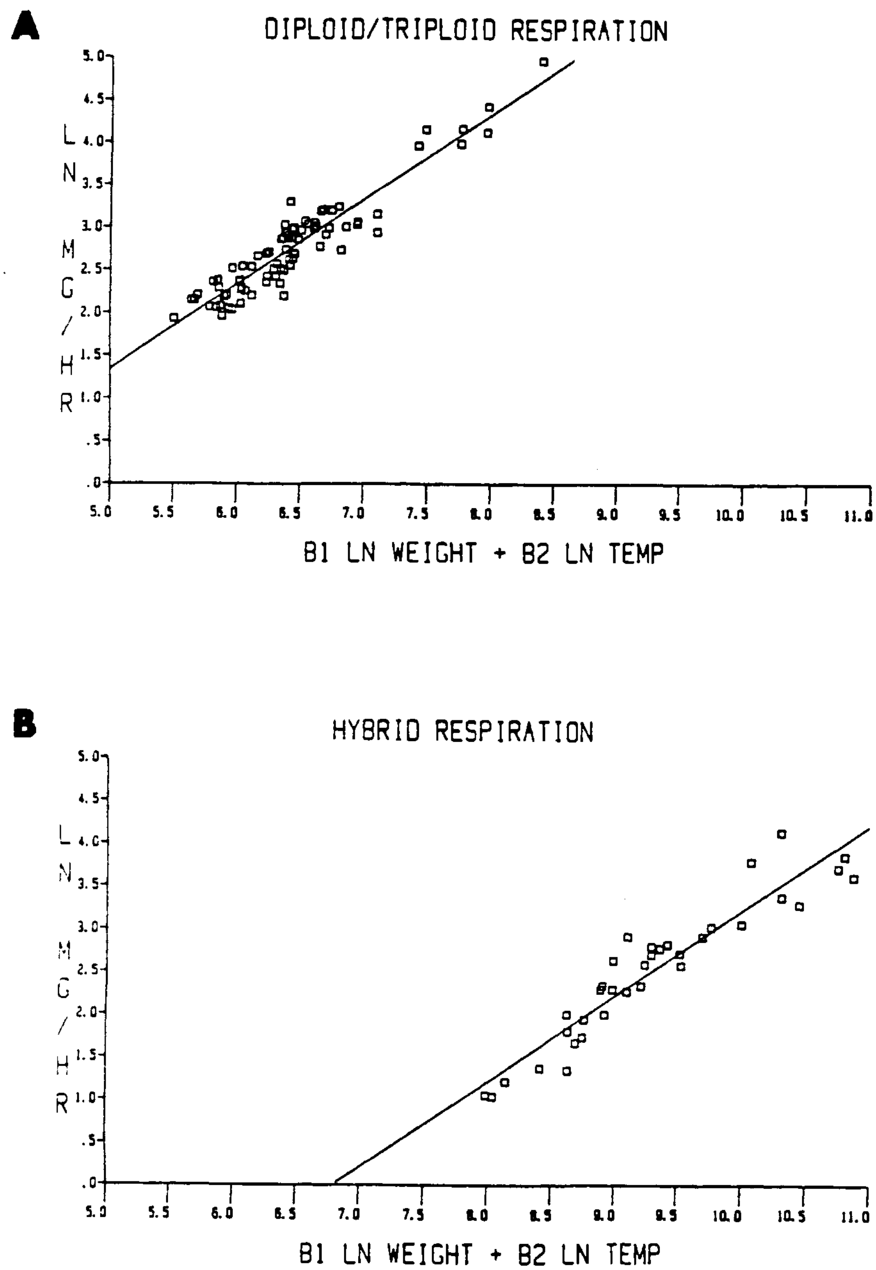


Fig. 3. Standard metabolism as a function of weight and temperature. A = diploid and triploid metabolism; B = hybrid metabolism.

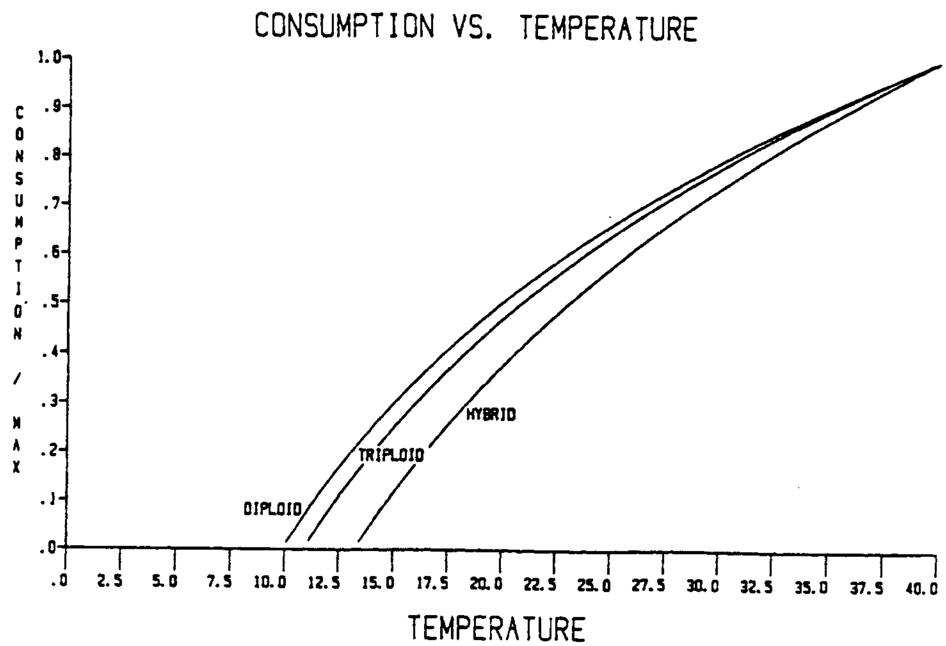


Fig. 4. Relative consumption rate as a function of temperature for hybrid carp, and triploid and diploid grass carp.

Table 3. Analysis of covariance for diploid-triploid regressions of consumption on temperature.

	Analysis of Covariance		
Group	d.f.	SS	MS
Diploid	21	0.30774	0.01465
Triploid	37	0.34742	0.00937
F = 1.55			
Pooled regression			
	58	0.55515	0.112958
	60	0.73560	0.01226
Difference	2	-0.08044	0.04022
F (2,58) = 3.561			

Overall, the energetic analyses indicate that the triploid grass carp would be superior to the hybrid as a substitute for the normal diploid grass carp. While the triploid grass carp is not exactly equivalent to the diploid in terms of control potential, it is very nearly so and appears to be a strong candidate for use in Illinois as a biological control agent. A much more detailed analysis and discussion of these studies can be found in Part 2: Chapter 1 of this report.

Plant Preferences and Consumption Rates

The rate at which herbivorous carp consume different aquatic macrophytes is known to vary considerably, as does the degree to which different plants are preferred (Fischer 1968, 1973). Although several preference or ranking lists have been published, little information is available on species of concern in Illinos or on differential consumption rates under standardized conditions. Since differential consumption may alter growth rates and necessarily affects the rate of plant removal a particular stocking might achieve, it was necessary in 1983 to estimate preferences and consumption rates for a number of plant species commonly problematic in Illinois (Part 2: Chapter 2).

Two experiments were conducted. In the first, hybrid and diploid grass carp were given repeated choices of 2-3 plant species combinations in specially designed holding tanks. Patterns of selection were then used to construct a ranking of nine plant species often controlled with herbicides in Illinois (Table 4). In the second experiment, each plant species was fed to hybrid and diploid grass carp sequentially to determine consumption rates for each species (Table 5). There was no difference in the relative preference for a given plant species between the hybrid and the grass carp, suggesting that relative preferences of the triploid grass carp would also be similar (preference experiments were not conducted with the triploid grass carp). Consumption rates were significantly correlated with relative preference, suggesting that fish chose plants with minimal handling times. Slender and brittle naiad (*Najas* spp.) were the most preferred, and coontail (*Ceratophyllum demersum*) the least. Consumption rates varied by

Table 4. Order of preference for grass carp and hybrids of nine common native Illinois macrophyte species.

Rank	Scientific name	Common Name
1	*Najas flexilis*	Slender naiad
2	*Najas minor*	Brittle naiad
3	*Chara* spp.	Chara
	Potamogeton foliosus	Leafy pondweed[1]
4	*Elodea canadensis*	American elodea
5	*Potamogeton pectinatus*	Sago pondweed
6	*Potamogeton crispus*	Curlyleaf pondweed
7	*Myriophyllum* spp.	Watermilfoil
8	*Ceratophyllum demersum*	Coontail

[1] Not compared with all other species, placement inferred

Table 5. Mean daily consumption in percent body weight per day for grass carp and hybrid carp during consumption rate study (individual tanks).

Plant species	% body weight consumed/day (mean ± SD)	Number of feeding periods	Total number of days	% loss/day in control
	Grass carp[1]			
Elodea canadensis	42± 4	6	20	2
Najas flexilis	41±11	4	9	4
N. minor	38± 6	4	10	6
Chara	36±17	3	11	4
Potamogeton pectinatus	30± 8	5	19	2
Ceratophyllum demersum	22± 5	4	14	3
Myriophyllum spp.	10± 3	7	7	2
	Hybrid carp[2]			
Najas flexilis	27± 8	8	10	4
Potamogeton pectinatus	23± 8	7	16	2
Najas minor	19±11	4	13	6
Elodea canadensis	16± 4	10	12	2
Ceratophyllum demersum	13± 5	5	11	2
Myriophyllum spp.	8± 4	11	11	3

[1] Data from 1 tank
[2] Data from 2 tanks

more than a factor of four. Elodea (*Elodea canadensis*) and curlyleaf pondweed (*Potamogeton crispus*) were consumed at the highest rates, while watermilfoil (*Myriophyllum* spp.) was consumed most slowly.

Reproductive Capacity

Functional sterility is a key issue in the selection of a possible substitute for the white amur. Induced triploidy in a normally diploid fish is almost always associated with reproductive incompetency. Unfortunately, absolutely guaranteeing that a particular type of triploid will never, under any circumstances, be capable of reproduction is extremely difficult, particularly when individual life spans are 10+ years and size ranges over four orders of magnitude. Each year since 1980 we have examined the gonadal development of our oldest triploid hybrids (1979 year class) looking for signs of reproductive capability. In all cases to date, the development of gonadal tissue in both males and females has been either extremely poor or nonexistent. In 1983, when our hybrids were 5 years old, they were treated with human chorionic gonadotropin (HCG) several weeks prior to their examination and showed no signs of sexual development; we conclude, therefore, that they are almost certainly incapable of natural reproduction (Table 6).

The extent to which triploid grass carp may be capable of reproduction is less certain. Polyploid fishes are almost always reproductively impaired (Purdom 1972, Allen and Stanley 1978). There is, however, no empirical evidence available for the grass carp since they have only recently become available in large quantities. Recent discussions by informed geneticists suggest that sterility is likely (American Fisheries Society Committee on Exotics) but advise continued work on empirical verification. A detailed discussion of these issues is presented in Part 2: Chapter 4.

Table 6. Total length (mm), sex, type of treatment, and gonadal development of bighead, grass, and hybrid carp in June 1982 and 1983. HGC = human chorionic gonadotropin; LH-RH_a = lutenizing-releasing hormone. IND = sex indeterminate. Gonadal development is reported as + for well developed but not flowing, - for developed, * for no development of gametes, and 0 for no development of gonads.

Carp	Year	Age	TL (mm)	Injection	Sex	Gamete Development
Bighead	1982	3+	360	None	F	-
		3+	330	HCG	F	-
		3+	480	None	F	-
		3+	530	None	M	*
	1983	4+	702	LH-RH_a	M	+
		4+	618	LH-RH_a	F	-
		4+	603	LH-RH_a	M	-
		4+	599	None	F	+
		4+	675	None	M	-
		4+	613	None	F	+
		4+	605	None	F	+
Grass	1982	3+	310	None	M	*
		3+	310	HCG	M	*
		3+	430	None	M	*
		3+	420	HCG	F	-
	1983	4+	606	LH-RH_a	M	+
		4+	574	LH-RH_a	F	+
		4+	510	LH-RH_a	M	*
		4+	612	None	M	*
		4+	570	None	F	*
		4+	558	None	F	*
Hybrid	1982	3+	350	None	IND	0
		3+	400	HCG	IND	0
	1983	4+	465	LH-RH_a	IND	0
		4+	445	LH-RH_a	IND	0
		4+	395	None	IND	0
		4+	437	None	IND	0

Field Trials

Stockings of herbivorous carp in Illinois Natural History Survey (INHS) experimental ponds verified predictions based on bioenergetic analyses that both grass carp and hybrid carp were capable of providing biological control of aquatic plant communities. Thirteen stocking experiments were performed during 4 years, using both the triploid hybrid and the diploid grass carp. Stocking levels ranged from 4 to 220 kg/ha (36-1,960 lbs/acre) (Table 7). For comparison, hybrid stocking densities were corrected to approximate grass carp equivalents, by multiplying by the inverse of the hybrid's proportional consumption rate (1/0.66 = 1.52). Given the very rigorous criterion of a major reduction in plant biomass within 4 months of stocking (Shireman 1984), both hybrids and grass carp provided significant control when stocked at levels in excess of 150 kg/ha (Fig. 5, Table 7). Ponds stocked at lower densities showed considerably less control, but peak effectiveness of low stocking densities generally are not apparent for 1-2 years (Shireman 1984; Part 3, this report).

The field trials also provided important data on mortality rates (Table 8). No significant differences between hybrid and diploid grass carp were found. Mortality rates were, however, highly size dependent, with carp under 200 g showing dramatically reduced survivorship (Fig. 6). Elevated mortality in the smaller size-classes was due to a combination of loss to largemouth bass and higher mortality immediately following stocking (presumably stress related). Once individuals reached 0.5 kg or more, mortality was very low. This size probably precludes bass predation, although it is unclear what the size threshold for escaping predation by piscivores might be in systems with larger predators, such as pike or muskie.

Overwintering mortality was generally low (Table 9). Mortality during the summer due to high temperatures and low oxygen concentrations was rare, although a large die-off of smaller 1981 triploids and diploids did occur in a high-density pond after a protracted period of high temperature, low dissolved oxygen concentration, and plant eradication (due to overgrazing).

Table 7. Seasonal average plant biomass, final biomass as a percentage of peak biomass, and stocking rate of carp for all study ponds.

Pond	Seasonal ave. plant biomass (g dry wt m-3)	Stocking rate of herbivorous carp (kg/ha)			Final plant biomass as % peak biomass
		Seasonal average	Stocking	Harvest	
LC1					
a	113.8	*	2.7	*	38
b	76.1	*	*	*	22
c	124.0	*	*	31.64	88
LC2	79.6	7.85	9.95	5.75	41
LC3	95.6	11.82	6.73	56.13	100
LC4	47.4	16.73	4.65	18.98	100
LC5	47.1	17.95	18.74	14.72	100
LC6	73.8	19.19	11.25	24.64	73
LC7	11.9	24.20	16.00	22.39	24
LC8	56.4	31.43	38.27	10.12	100
LC9	100.3	36.73	24.37	49.09	79
LC10	42.8	51.15	45.10	57.19	17
LC11	90.8	91.96	59.39	124.53	56
LC12	94.5	128.44	118.42	138.46	71
LC13	82.9	145.31	149.00	141.61	85
HC1	8.7	163.39	110.76	216.02	0
HC2	42.6	188.80	119.60	257.99	0
HC3	52.8	239.34	198.57	280.10	20
HC4	37.7	360.22	220.37	500.08	0
C1	60.0				97
C2	76.4				81
C3	140.2				53
C4	99.4				22
C5	84.1				52
C6	81.5				100
C7	40.4				55
C8	80.4				100
C9	74.8				81
C10	44.1				96
C11	54.5				100
C12	87.4				98

*Carp not stocked or censused

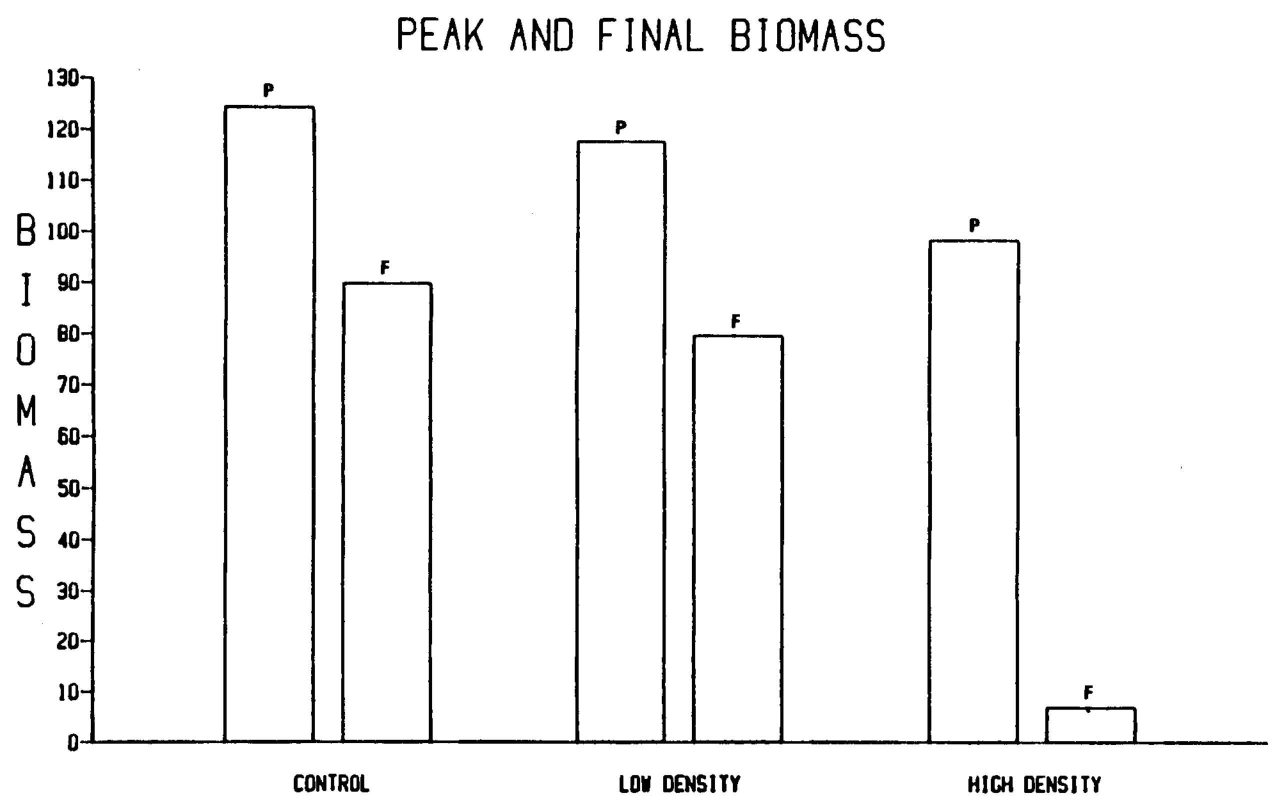


Fig. 5. Peak and final (September) macrophyte standing crop biomass (g dry weight m^{-3}) in all control, low density, and high density ponds.

Table 8. Growing mortality during field trials, 1981-1983.

Fish	Type	Year class	Growing season	Mean weight		Number		Number of days	% loss
				Stocking	Census	Stocking	Census		
Hybrid	(2N)	1980	1981	67	364	8	6	154	25
Hybrid	(3N)	1980	1981	140	278	10	3	92	70
Hybrid	(3N)	1980	1981	158	257	20	9	95	55
Hybrid	(3N)	1980	1981	148	287	10	4	95	60
Hybrid	(3N)	1980	1981	159	219	20	1	92	95
Hybrid	(3N)	1980	1981	145	283	30	11	94	63
Hybrid	(3N)	1980	1981	159	267	30	6	102	80
Hybrid	(2N)	1980	1982	349	488	5	5	166	0
Hybrid	(3N)	1980	1982	278	610	5	5	168	0
Hybrid	(3N)	1980	1982	321	674	21	21	173	0
Hybrid	(3N)	1981	1982	30	345	25	18	187	28
Hybrid	(3N)	1981	1982	33	172	160	77	115	52
Hybrid	(3N)	1981	1982	33	218	150	29	147	81
Hybrid	(3N)	1981	1982	30	116	100	9	185	91
Hybrid	(3N)	1981	1982	28	280	150	4	166	97
Hybrid	(3N)	1981	1982	28	412	75	4	137	95
Hybrid	(3N)	1981	1982	32	362	75	15	166	80
Hybrid	(3N)	1981	1982	35	505	25	1	137	96
Hybrid	(3N)	1979	1983	904	888	14	13	144	7
Hybrid	(3N)	1980	1983	711	843	3	3	144	0
Hybrid	(3N)	1980	1983	486	456	3	3	144	0
Hybrid	(3N)	1980	1983	673	875	20	18	164	10
Hybrid	(3N)	1981	1983	256	386	95	85	141	6
Grass	(3N)	1981	1983	36	419	100	15	117	85
Grass	(3N)	1981	1983	33	536	117	30	195	70
Grass	(3N)	1981	1983	582	1322	28	28	140	0

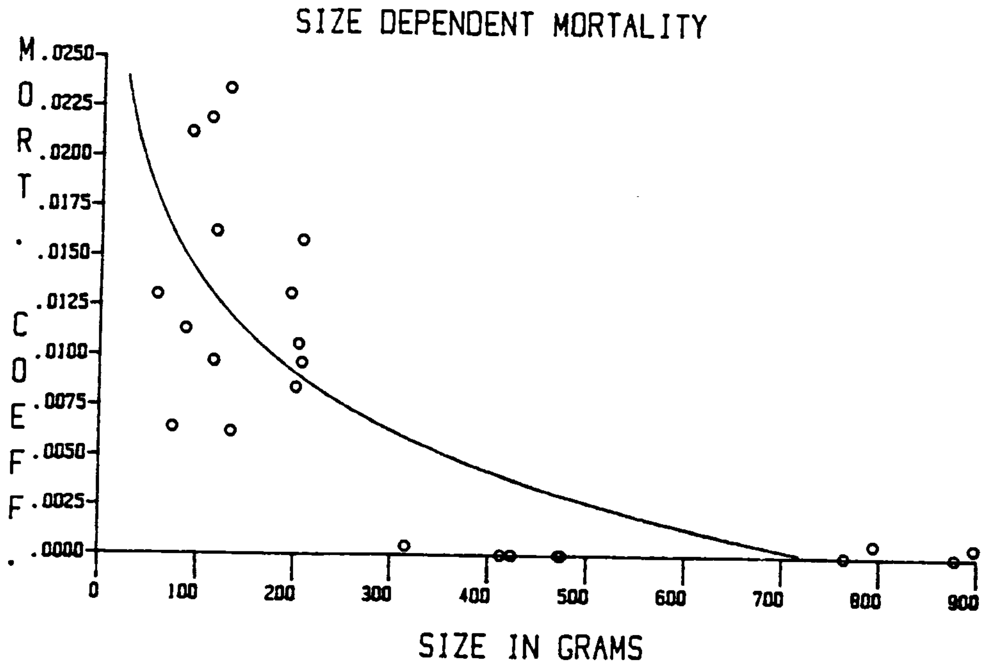


Fig. 6. Survivorship of stocked herbivorous carp as a function of size.

Table 9. Overwinter mortality during field trails, 1981-1983.

Fish	Type	Year class	Winter	Number: Stocking	Number: Census	% loss	Mean weight in fall (g)
Hybrid	(2N,3N)	1980	1980-81	364	279	27	18
Hybrid	(2N,3N)	1980	1981-82	31	31	0	279
Hybrid	(2N,3N)	1980	1982-83	27	26	4	591
Hybrid	(3N)	1981	1982-83	56	53	5	279
Hybrid	(3N)	1981	1982-83	77	76	1	172
Grass carp	(3N)	1981	1982-83	37	37	0	478

Ecological Impacts

The environmental impacts of using herbivorous carp are mostly indirect, resulting primarily from the removal of macrophytic plants from lentic ecosystems. Nevertheless, these impacts can be quite dramatic and, in some cases, the presence of large numbers of fish may aggravate them. In addition to 13 ponds stocked with carp, we carefully monitored a series of control ponds to provide a large statistical base for analyses of carp impacts. In the experimental design, all ponds studied over the past 4 years are grouped into three treatment categories: control, low-density carp stocking (<150 kg/ha grass carp equivalents), and high-density carp stocking (>150 kg/ha). Standard statistical techniques were then used to test for significant treatment effects. By grouping data in this way, we included the large component of natural pond-to-pond and year-to-year variation in the control treatment and maximized replication to increase the statistical power of our analyses.

In ponds stocked at lower densities there were some significant, although not necessarily dramatic, differences in water chemistry. For 12 of 20 (60%) parameters routinely measured (Tables 10, 11, and 12), low stocking density treatments had concentrations significantly different from those of control ponds. Differences were mainly attributable to reductions in plant productivity, and included slight reductions in daytime pH and total and dissolved carbon; and increases in alkalinity, CO_2, nutrient (nitrogen and phosphorus) concentrations, and total dissolved solids. There was also some increase in chlorophyll concentrations, indicating a response in the phytoplankton populations.

In high stocking density ponds, similar but more dramatic trends were observed, with 90% of the measured water quality parameters showing statistically significant differences from the control group (Tables 10, 11, and 12). The most important differences were decreased dissolved oxygen and organic carbon concentrations and increased CO_2 concentrations (Fig.

Table 10. Results of SNK analysis for field chemistry parameters (mg/L unless otherwise noted) in Annex ponds. Treatment means (± standard error) are given, with the number of samples in parentheses. A dash (-) joins groups with no significant difference and an asterisk(*) indicates significantly different treatment.

	Control		Low Density		High Density
Surface water temperature (C)	23.94±0.34 (145)	-	23.31±0.27 (173)	-	24.15±0.57 (44)
Surface dissolved oxygen	8.41±0.17 (147)	-	8.12±0.17 (179)		6.94±0.37* (44)
Bottom dissolved oxygen	6.07±0.29 (146)	-	6.68±0.24 (177)		3.53±0.49* (44)
pH	8.85±0.06* (130)		8.44±0.06* (150)		7.75±0.12* (22)
Free carbon dioxide	1.03±0.25* (118)		3.17±0.42* (146)		9.02±2.03* (10)
Alkalinity	117.54±2.48* (128)		149.09±3.88 (146)	-	151.00±10.49 (20)
Total dissolved solids	216.63±2.24* (118)		242.87±3.76* (146)		287.00±2.84* (10)
Specific conductance (umhos/cm)	291.20±3.12* (118)		331.34±5.69* (146)		388.70±4.05* (10)
Vertical extinction coefficient[1]	2.25±0.09 (84)		2.08±0.06 (171)		2.53±0.13 (48)

[1] Control not significantly different from low density pond; control not significantly different from high density pond; control and low density pond significantly different from high density pond.

Table 11. Results of SNK analysis on pigments (mg/L) for all ponds and for Annex ponds only. Treatment means (± standard error) are given, with the number of samples in parentheses. A dash (-) joins groups with no significant difference and an asterisk(*) indicates significantly different treatment.

	Control		Low Density		High Density
All ponds					
Chlorophyll *a*	11.90±0.84	-	12.67±0.87	-	15.51±1.48
	(382)		(456)		(100)
Phaeophytin	3.23±0.29	-	3.12±0.58	-	5.22±0.42
	(382)		(456)		(100)
Total chlorophyll	22.11±1.74	-	21.42±1.68	-	26.01±2.27
	(228)		(424)		(100)
Annex ponds only					
Chlorophyll *a*	7.32±0.54*		12.01±0.97*		15.51±1.48*
	(282)		(372)		(100)
Phaeophytin[1]	2.31±0.15		3.23±0.71		5.22±0.42
	(282)		(372)		(100)
Total chlorophyll[1]	15.24±1.15		20.46±1.92		26.01±2.27
	(188)		(356)		(100)

[1] Control pond not significantly different from low density pond; low density pond not significantly different from high density pond; those two groups were significantly different.

Table 12. Results of SNK analysis for laboratory chemistry parameters (mg/L) in Annex ponds. Treatment means (± standard error) are given, with the number of samples in parentheses. A dash (-) joins groups with no significant difference and an asterisk(*) indicates significantly different treatment.

	Control n=160		Low Density n=158		High Density n=46
Total carbon	26.20±0.85*		18.71±0.73	-	18.18±0.98
Particulate carbon	2.77±0.20	-	2.61±0.21	-	3.30±0.40
Dissolved organic carbon	19.65±0.76*		13.51±0.51	-	14.88±0.73
Inorganic carbon	22.50±0.50*		28.38±0.71*		35.38±1.85*
Total phosphorus	0.08±0.00*		0.09±0.00	-	0.10±0.01
Soluble orthophosphate	0.04±0.00	-	0.04±0.00		0.06±0.01*
Nitrate[a]	0.04±0.00		0.03±0.00		0.03±0.00
Ammonia[b]	0.16±0.01		0.11±0.01		0.14±0.01

[a] Low density and control ponds not significantly different from high density ponds control significantly different from low density ponds.
[b] Control not significantly different from high density ponds; low density ponds significantly different from control and high density ponds.

7), planktonic algae, turbidity (Fig. 8), and increased nutrient concentrations (Fig. 9).

Sedimentation rates also increased in ponds stocked with herbivorous carp (Table 13). In ponds stocked so heavily that all plants were removed (overgrazed), the increases in sedimentation rates were phenomenal, with daily accumulation more than 22 times higher than that in adjacent control ponds (Fig. 10). These increases in sediment deposition in overgrazed ponds were apparently due both to the high rate of fecal production by carp and to the continuous resuspension of the bottom by the carp as they rooted for vestigal plant matter, rhizomes, and possibly benthic algae and invertebrates.

Microbial populations in the sediments were also significantly elevated in the high stocking density ponds (Table 14) and concentrations in the water were significantly higher in the one overgrazed pond examined. Related to this sedimentation effect was a near catastrophic decline in benthic invertebrate populations in overgrazed ponds. Both population sizes and species diversity declined (Table 15) in high stocking density ponds; a similar, but not statistically significant trend was observed in low stocking density ponds.

The impact of herbivorous carp on sport fishes varied between species. Bluegill production declined dramatically (Table 16), particularly in high density treatments. Catfish production, on the other hand, increased significantly; this contrast is indicative of the kind of shift in sport fisheries that might be expected with large-scale introductions of herbivorous carp. The response of largemouth bass populations was more complicated, but was basically consistent with the predictions of our trophic-level model (Wiley et al. 1983). Fingerling and breeder bass production increased significantly (Table 16) in low density carp ponds, and decreased in high density ponds. Thus the highest average levels of piscivorous bass production were observed in the ponds with intermediate levels of plant control. Young-of-the-year bass had the highest productivity in high density ponds although none of the treatments varied by more than 20%.

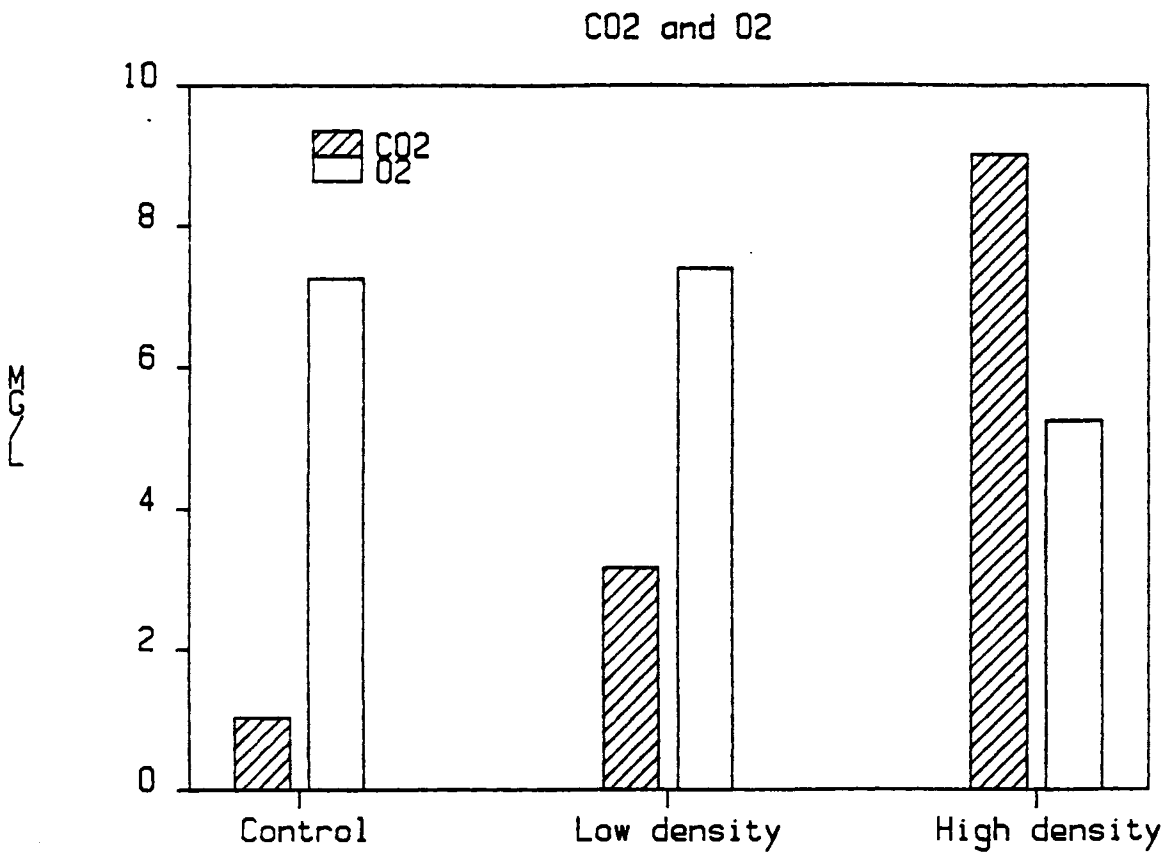


Fig 7. Free carbon dioxide (mg/L) and dissolved oxygen (mg/L) in control, low density, and high density ponds at the Annex site.

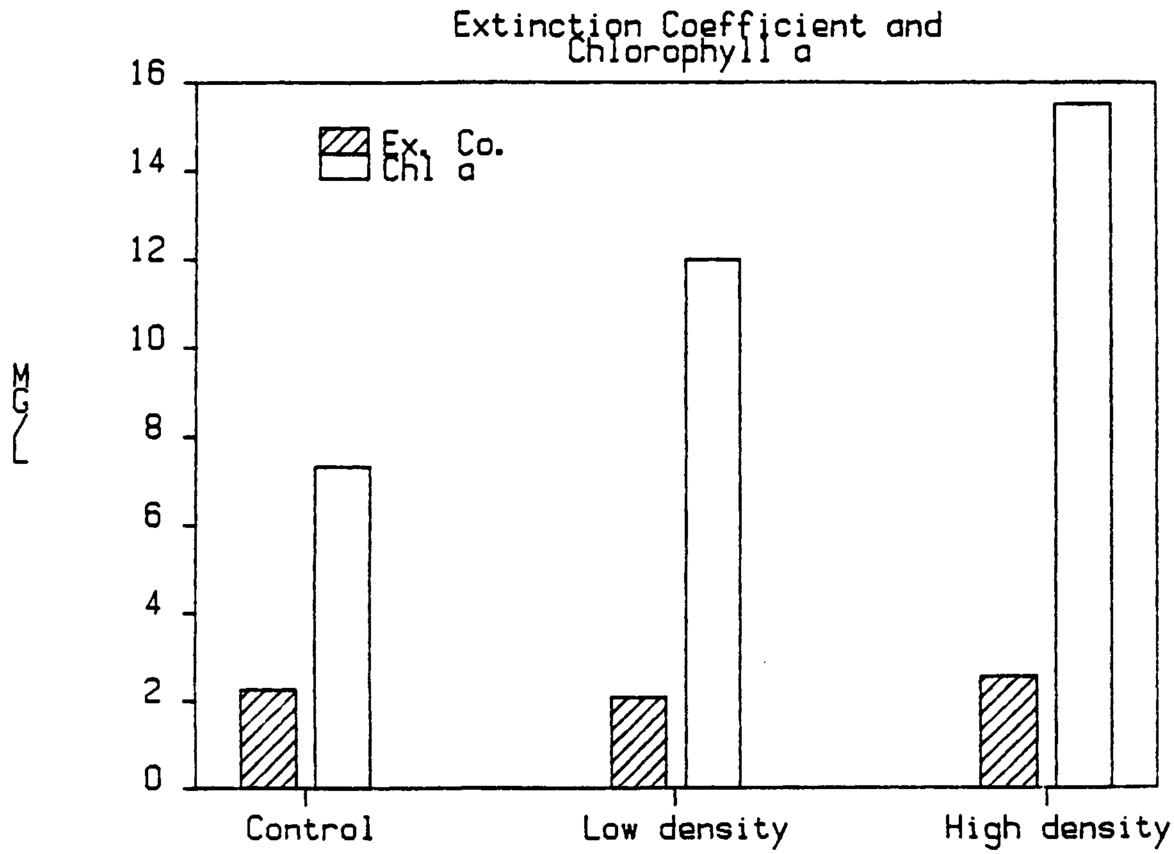


Fig. 8. Extinction coefficient and chlorophyll a concentration (mg/L) in control, low density, and high density ponds at the Annex site.

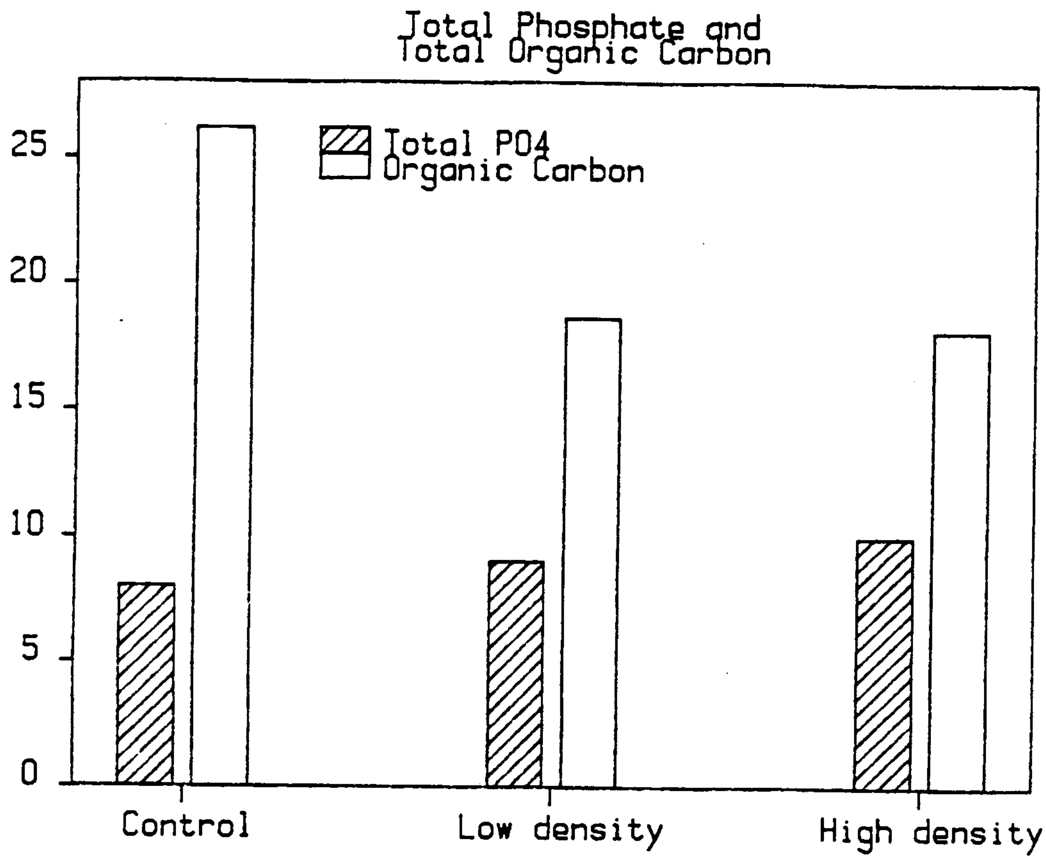


Fig. 9. Total phosphate (mg/L x 100) and organic carbon (mg/L) in control, low density, and high density ponds at the Annex site.

Table 13. Sedimentation rates (g dry weight m^{-2} day^{-1}) in control, low and high density ponds. All data are means of four replicates.

Pond	Seasonal average carp biomass	Sedimentation rate June	July	September
C7	-	0.48	0.72	0.99
C8	-	0.91	0.81	0.53
C12	-	0.29	0.52	0.39
LC6	145.31	-	-	1.29
LC11	128.44	0.21	0.28	3.11
LC12	91.96	-	-	3.15
HC3	239.34	3.49	2.53	3.26
HC4	360.22	4.23	9.51	22.19

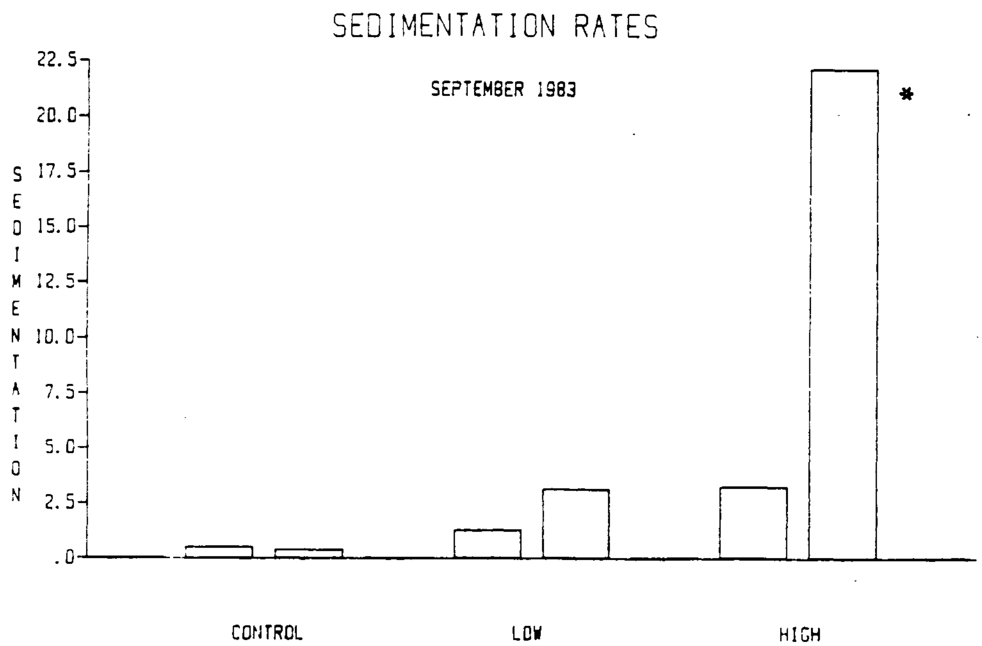


Fig. 10. Sedimentation rates (g dry weight m^{-2} per day) in control, low density, and high density ponds in 1983. The overgrazed pond is denoted by an asterisk (*).

Table 14. Comparison of sediment microbial populations (CGU) in control, low, and high density pond groups. Treatment means (± standard error) are given, with the number of samples in parentheses. A dash (-) joins groups with no significant difference and an asterisk(*) indicates significantly different treatment.

Analysis of Variance

Source	d.f.	SS	MS	F
Between	2	4.5×10^{13}	2.25×10^{13}	10.02***
Within	311	7.0×10^{14}	2.25×10^{13}	
Total	313	7.45×10^{14}		

P = 0.000
Kruskal Wallis p = 0.000, H = 24,855

SNK Results

Control		Low Density	High Density
1.5×10^{6} (194)	-	1.8×10^{6} (96)	2.9×10^{6}* (24)

Table 15 . Results of one-way analyses of variance and SNK multiple range tests, by treatment, upon the densities (no. m^{-2}) (mean ± standard error) of major taxonomic groups of infaunal invertebrates.

Taxa	Control (n = 12)		Low Density (n = 11)		High Density (n = 8)	Alpha Value	F
Nematoda	925.92± 627.99		1085.91± 633.96		2708.38±1338.14#	0.058[b]	3.16
Oligochaeta	602.00± 355.02	-	328.36± 186.63	-	208.50± 101.74	0.579	0.56
Amphipoda	1365.75± 806.54	-	959.64± 453.12	-	69.50± 45.50	0.363	1.05
Gastropoda	138.92± 115.96	-	151.55± 151.55	-	0.00± 0.00	0.668	0.41
Aquatic Acari	162.17± 63.64	-	378.91± 136.47	-	347.25± 125.84	0.303	1.25
Ephemeroptera	2430.58±1332.19	-	1818.45±1172.70	-	416.63± 165.97	0.498	0.71
Zygoptera	23.17± 23.17	-	75.82± 54.20	-	0.00± 0.00	0.361	1.06
Trichoptera	579.08± 222.92	-	176.82± 86.01	-	34.75± 34.75	0.059	3.13
Coleoptera	69.50± 49.88	-	75.82± 39.15	-	0.00± 0.00	0.424	0.89
Ceratopogonidae	787.33± 246.20	-	2121.27± 549.51	-	660.00± 196.00	0.060[a]	
Chironomidae	10902.75±2172.51		7904.00±1621.14		3020.75±1216.99#	0.025	4.20
Total organisms	18194.50±4146.32	-	15126.18±3142.74		7604.00±1644.96*	0.057[b]	3.17
Number of taxa/ sample	15.50± 2.12		13.91± 1.67		8.38± 1.94#	0.055	3.22
Diversity	1.20± 0.08	-	1.14± 0.08	-	0.87± .16	0.092	2.60
Evenness	0.50± 0.02	-	0.48± 0.02	-	1.67± 1.19	0.252	1.45

[a] = variances heterogeneous (by Cochrans C test); analysis of variance performed using Kruskal-Wallis one-way test
[b] = analysis of variance performed upon transformed (log(x+1)) data
* = treatment mean significantly different from all other treatment means
\# = high density treatment mean significantly different from control treatment mean
\- = joined groups having no significant difference

Table 16. Summary of analysis of variance results for sport fish production estimates (kg/ha) for control, low density, and high density ponds at the Annex site. Treatment means (± standard error) of all years (except where noted) are given, with the number fish harvested over that period in parentheses. A dash (-) joins SNK groups with no significant difference and an asterisk(*) indicates significantly different treatment at the 0.05 level.

	Control	Low Density	High Density	F	Alpha value
Largemouth bass					
Young-of-the-year[1]	19.66±0.08* (2474)	16.99±0.18* (2601)	20.80±0.49* (1226)	79.499	0.000
Fingleriing (3-5")[2]	33.17±0.32* (92)	35.20±0.27* (111)	31.00±0.58* (35)	27.017	0.000
Breeder (7"+)	9.86±0.23* (46)	14.81±0.48 - (36)	13.33±0.61 (11)	42.688	0.000
Bluegill					
Young-of-the-year[1]	79.99±0.27* (15,256)	59.76±0.14* (19,138)	28.24±0.37* (2251)	511.566	0.000
Breeder (4"+)	9.37±0.18* (56)	7.52±0.22 - (54)	7.54±0.35 (19)	21.150	0.000
Channel catfish					
4"	5.18±0.13* (21)	5.75±0.11* (20)	10.01±0.30* (12)	150.347	0.000
6"	7.77±0.12* (41)	9.23±0.15* (31)	12.84±0.42* (12)	118.674	0.000
8"	10.76±0.17* (47)	11.94±0.18* (34)	14.91±0.59* (11)	41.565	0.000

1 1982-1983 estimates only
2 1981-1983 estimates only

Average seasonal growth followed a pattern similar to that of production (Table 17), except growth increments of young-of-the-year bluegills increased with carp stocking, presumably a response to lower population densities. Condition factors increased with increasing carp densities (Table 18) for all species; although this trend was statistically significant only for young-of-the-year, these results were unexpected and may have resulted from a short-term increase in prey vulnerability as macrophyte stands were eliminated.

Survivorship of stocked fishes did not differ significantly across treatments (Table 19). However, numerical young-of-the-year (YOY) recruitment of centrarchids declined in ponds stocked with herbivorous carp, dramatically so in the overstocked pond (HC4) (Fig. 11). While high variances in the control group of ponds obscured any statistical significance, these declines were undoubtedly ecologically important; in fact, they were the basis for observed statistically significant declines in YOY production in the carp ponds (Fig. 12, Table 16). This reduced recruitment seems primarily the result of increased predation with reduction in plant cover and was not the result of any failure to successfully spawn.

Our experimental design, while giving us substantial statistical power in analyzing single season responses of fish populations, did not provide any direct information on possible long-term impacts. To assess these long-term consequences we are forced to rely on the predictions of a theoretical model derived for this purpose (Wiley et al. 1983). Our model suggests that major suppression of aquatic macrophyte populations over several growing seasons will result in major reductions in centrarchid production; initially bluegills will be most severely affected, and finally bass populations as well. Since trends along these lines were already apparent in the single season experiments, the model's basic predictions seem accurate. It should be noted, however, that in situations where there are pelagic forage fish available as a substitute for sunfishes (e.g., gizzard shad), bass production may be insulated from

Table 17. Summary of sport fish weights (g) in Annex ponds at stocking and harvest and the change in mean weight over the growing season. Treatment means (± standard error) of all years (except where noted) are given, with sample size in parentheses. Analysis of variance comparisons and SNK groupings are given for change in weight. Dashes (-) join groups not significantly different; asterisks (*) indicate differences at the 0.05 level of significance.

	Stocking (g)			Harvest (g)			Change in weight (g)				
	Control	Low density	High density	Control	Low density	High density	Control	Low density	High density	F	Alpha value
Largemouth bass											
Breeder (7"+)	185.48± 5.85 (48)	181.11±12.17 (38)	144.00± 5.78 (12)	302.76±10.35 (46)	375.25±10.32 (36)	325.08±10.70 (11)	117.28±11.85* (46)	184.14±15.86- (36)	181.08±12.28 (11)	6.869	0.002
Fingerling[1] (3-5")	13.76± 0.72 (100)	16.51± 0.83 (120)	11.21± 0.39 (40)	124.88± 4.87 (73)	149.49± 3.05 (97)	140.17± 4.60 (35)	111.12± 4.94* (73)	132.98± 3.18- (97)	129.05± 4.70 (35)	8.316	0.000
Young-of-the-year[2]	—	—	—	2.63± 0.07 (400)	3.06± 0.17 (510)	4.53± 0.36 (166)	2.63± 0.07- (400)	3.06± 0.17 (510)	4.53± 0.36* (166)	19.182	0.000
Bluegill											
Breeder (4"+)	75.02± 3.74 (80)	79.35± 3.10 (60)	67.70± 2.39 (20)	151.81± 4.56 (56)	138.85± 4.63 (54)	127.42± 2.88 (19)	76.89± 6.38- (56)	59.50± 5.72- (54)	59.72± 3.86 (19)	2.607	0.078
Young-of-the-year[2]	—	—	—	1.46± 0.05 (400)	1.10± 0.04 (500)	1.67± 0.11 (239)	1.46± 0.05* (480)	1.10± 0.04* (500)	1.67± 0.11* (239)	22.063	0.000
Channel catfish											
4"	10.23± 0.67 (47)	10.92± 0.33 (38)	10.00± 0.81 (12)	115.19± 8.08 (21)	106.75± 6.75 (20)	138.75± 5.44 (12)	104.96± 8.15 (21)	95.83± 6.76 (20)	128.75± 5.50 (12)	3.863	0.028[b]
6"	25.44± 0.93 (48)	25.25± 1.94 (38)	26.25± 1.45 (12)	123.34± 8.27 (41)	151.10± 6.89 (31)	191.25± 7.52 (12)	87.90± 8.33* (41)	125.85± 7.20* (31)	165.00± 7.66* (12)	10.010	0.000
8"	53.33± 1.89 (48)	53.56± 2.25 (36)	51.08± 2.26 (12)	178.83±12.00 (47)	206.41± 6.48 (34)	250.00±12.34 (11)	125.50±12.15 (47)	152.85± 8.77 (34)	198.92±12.56 (11)	5.066	0.008[a]

[1] 1981–1983 data only

[2] 1982–1983 data only

[a] Control is significantly different than the high density treatment; low density treatment not significantly different from either group.

[b] High density treatment is significantly different from low density treatment; control is not significantly different from either group.

Table 18. Summary of sport fish condition factors (K) in Annex ponds at stocking and harvest and the change in condition over the growing season for all years (except where noted). Treatment means (± standard error) of all years (except where noted) are given, with sample size in parentheses. Analysis of variance comparisons and SNK groupings are given for change in condition. Dashes (-) join groups not significantly different; asterisks (*) indicate differences at the 0.05 level of significance.

	Stocking (K)			Harvest (K)			Change in condition (K)				
	Control	Low density	High density	Control	Low density	High density	Control	Low density	High density	F	Alpha value
Largemouth bass											
Young-of-the-year[1]	—	—	—	1.000±0.010 (400)	1.072±0.010 (510)	1.115±0.024 (166)	1.000±0.010* (400)	1.072±0.010* (510)	1.115±0.024* (166)	17.867	0.0000
Fingerling (3-5")[2]	1.021±0.014 (100)	1.051±0.014 (120)	1.142±0.018 (40)	1.279±0.011 (92)	1.316±0.013 (111)	1.422±0.027 (35)	0.258±0.018 - (92)	0.265±0.018 - (111)	0.300±0.033 (35)	0.612	0.5432
Breeder (7"+)	1.230±0.016 (48)	1.272±0.030 (38)	1.159±0.031 (12)	1.314±0.012 (46)	1.387±0.018 (38)	1.382±0.032 (11)	0.084±0.020 - (46)	0.115±0.035 - (38)	0.223±0.045 (11)	2.752	0.0694
Bluegill											
Young-of-the-year[1]	—	—	—	1.368±0.020 (400)	1.417±0.025 (500)	1.860±0.074 (239)	1.368±0.020 - (400)	1.417±0.025 (500	1.860±0.074* (239)	44.753	0.0000
Breeder (4"+)	2.113±0.047 (80)	1.849±0.029 (60)	1.829±0.033 (20)	2.216±0.048 (56)	2.084±0.035 (54)	2.163±0.059 (19)	0.103±0.074 - (56)	0.235±0.046 - (54)	0.334±0.052 (19)	2.408	0.0942
Channel catfish											
4"	0.683±0.028 (47)	0.611±0.014 (36)	0.608±0.048 (12)	0.749±0.014 (21)	0.737±0.012 (20)	0.770±0.016 (12)	0.066±0.042 - (21)	0.126±0.022 - (20)	0.162±0.051 (12)	1.433	0.2489
6"	0.639±0.023 (48)	0.640±0.057 (36)	0.572±0.014 (12)	0.738±0.011 (41)	0.716±0.014 (31)	0.754±0.017 (12)	0.099±0.027 - (41)	0.076±0.063 - (31)	0.182±0.022 (12)	0.744	0.4786
8"	0.608±0.012 (48)	0.583±0.010 (36)	0.574±0.009 (12)	0.740±0.011 (47)	0.732±0.012 (34)	0.736±0.013 (11)	0.131±0.016 - (47)	0.139±0.015 - (34)	0.162±0.016 (11)	0.400	0.8719

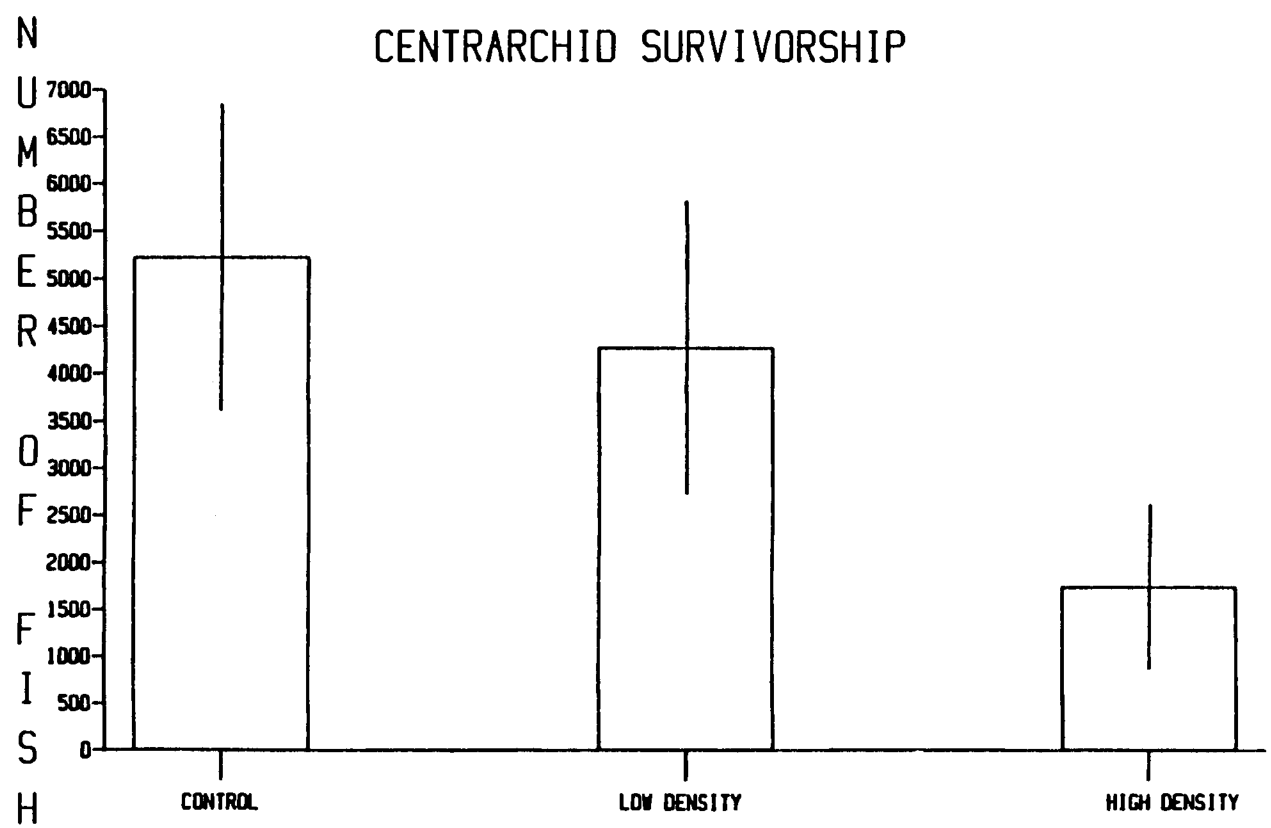
1 1982-1983 data only
2 1981-1983 data only

Table 19. Summary of ANOVA comparisons and SNK groupings for sport fish survivorship in Annex ponds all years. Mean survivorship (calculated as the ratio of number harvested to number stocked) (± standard error) is reported along with the alpha value and F statistic. Dashes (-) join groups with no signficant difference.

	n at stocking	Control	Low Density	High Density	F	Alpha Value
Largemouth bass						
Breeder	6	0.96±0.04-	1.00±0.00-	0.92±0.08	0.71	0.51
Fingerling[a]	20	0.81±0.08-	0.93±0.05-	0.88±0.03	0.79	0.47
Bluegill						
Breeder	10	0.71±0.09-	0.90±0.04-	0.95±0.05	2.25	0.15
Channel catfish						
4"	6	0.44±0.12-	0.56±0.15-	1.00±0.00	2.15	0.16
6"	6	0.85±0.08-	0.86±0.11-	1.00±0.00	0.33	0.73
8"	6	0.98±0.02-	0.94±0.04-	0.92±0.08	0.70	0.51

[a] 15 fish were stocked in 1980

Fig. 11. Centrarchid young-of-the-year recruitment (numbers at draining) in control, low density, and high density ponds at the Annex site in 1983.



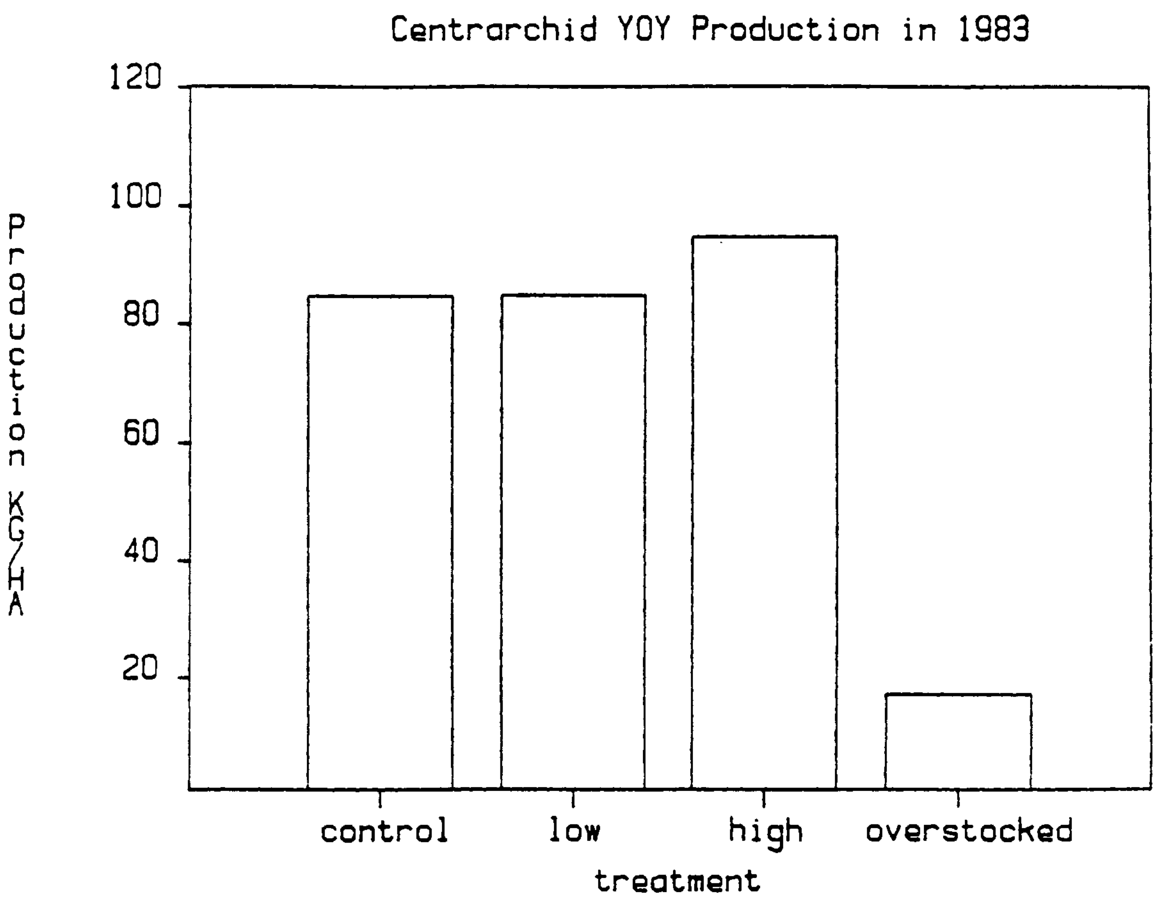


Fig. 12. Production (kg/ha) of young-of-the-year centrarchids in control, low density, high density, and overstocked ponds at the Annex site in 1983.

the effects of macrophyte loss. In waters with pike populations, a similar long-term reduction in productivity is likely if macrophyte populations are eliminated entirely.

Stocking Recommendations

As previously described, growth and consumption rates of herbivorous carp vary widely with temperature, size, and food availability and type. As a result, the amount of control achieved by a particular stocking level also varies with these factors. Thus, reasonable stocking densities in southern Illinois may be less than effective in the northern part of the state. Likewise, stocking densities sufficient to control curlyleaf pondweed may be insufficient to control similar-sized populations of watermilfoil. Our approach to the complexities of recommending stocking rates for the whole state of Illinois has been to use bioenergtic and field data to generate a computer-implemented stocking model. The model is capable of simulating the growth and control potential of herbivorous fish under a variety of climatic and plant-species combinations (Fig. 13). Using this model, we generated standardized stocking tables and graphs (Fig. 14) which can serve as general guides throughout the state. The model has also been useful in comparing the efficacy and costs of various stocking strategies. Stocking recommendations, an analysis of serial versus batch stocking strategies, and a detailed description of the Illinois Herbivorous Fish Stocking Simulation System (IHF3S) are given in Part 3 of this report.

Chemical Versus Biological Control

There are two key issues to be considered in any comparison of herbivorous carp and herbicides: cost effectiveness and environmental impact. In terms of cost effectiveness, herbivorous carp are clearly superior to chemical controls, if the comparison is made over the long-term (i.e., 5-10 years) and the particular species of plants to be controlled are both relatively dominant and palatable. Under these conditions, the cost of equivalent control using commercially available herbicides is 5-20 times higher than that of using triploid grass carp (Table 20). There is then a substantial

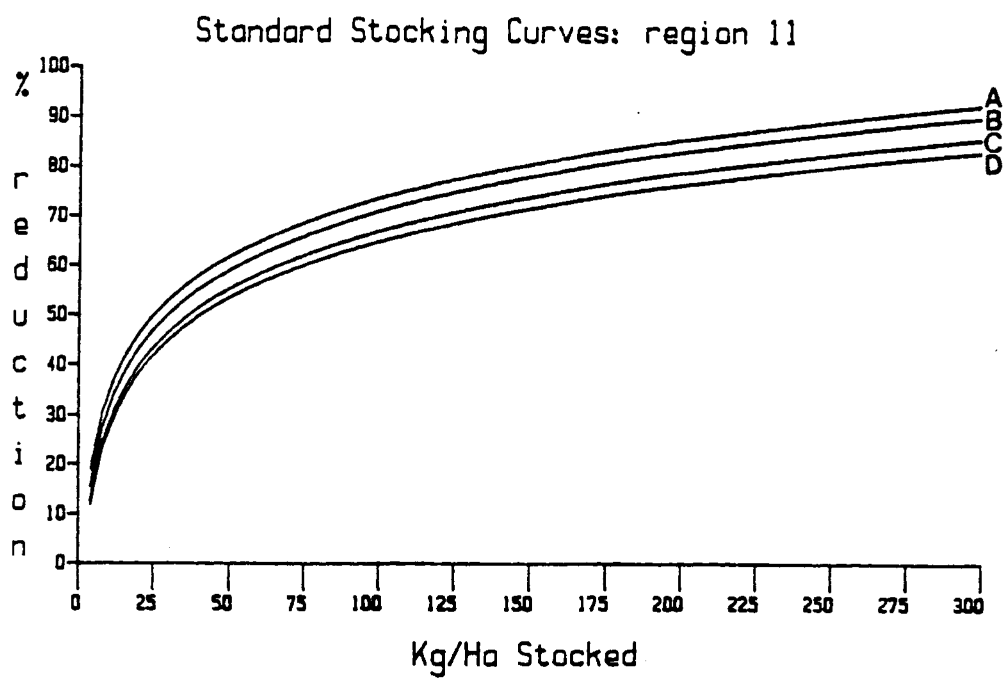


Fig. 13. Standing stocking curve for triploid grass carp in Region 11 feeding on Potamogeton crispus and Najas spp. community. Stocking density (kg/vegetated ha) is plotted against 10-year mean reduction in biomass. A = 50 kg fish, B = 100 kg fish, C = 200 kg fish, D = 400 kg fish. g fish

YEAR	FNUM	SIZE	KG/HEC	CONS/PROD		AVEPEAK		AVEBIOMASS	PEAK
0	47	200	95	0	0	0	0		
1	21	959	201	16		186155.1		36543.65	186155.1
2	15	1093	164	58		99287.95		21201.38	12420.73
3	10	1680	168	51		71821.89		16420.20	16889.80
4	7	2857	200	59		57181.37		13858.47	13259.76
5	5	4940	247	56		48799.17		12437.41	15270.39
6	3	7762	232	54		43701.63		11567.00	18214.01
7	2	11955	239	41		41603.87		11185.72	29017.35
8	1	18080	180	21		43515.15		11602.82	56894.09
9	1	20980	209	5		56960.46		15350.49	164522.9
10	1	22374	223	3		69787.21		18900.18	185228.0

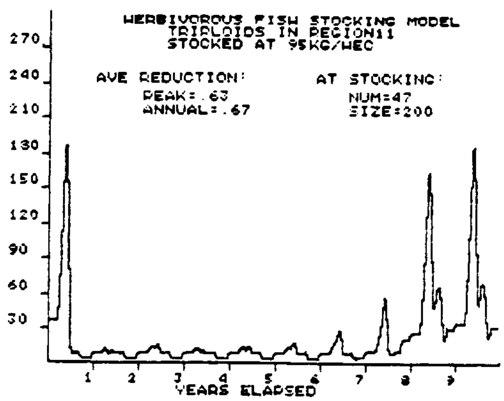


Fig. 14. Simulated plant populations (kg/ha) over 10 years after stocking grass carp. Example of the output from the Illinois Herbivorous Fish Stocking Simulation System (IHF3S).

economic incentive to use biological control--an incentive that will probably lead to a large market demand relatively quickly after any announcement of legalization.

Comparing relative environmental risk requires that a distinction be drawn between the potential for ecological damage and for toxicological damage. Herbicides, of course, carry a certain risk of chronic contamination of aquatic systems by low levels of degradation products and/or manufacturing contaminants. These risks are very difficult to assess, are highly controversial, and are beyond the scope of the present study. Nevertheless, this potential complication of herbicide use should be noted, particularly since it places certain constraints on the use of chemical herbicides; for example, application of most herbicides is illegal in bodies of water used for public drinking supply.

Acute ecological damage can be assessed experimentally. In this regard both chemical and biological control must be considered potent technologies capable of major ecological disruption if not carefully used. In three separate herbicide experiments conducted during this project for comparison with herbivorous carp stocking, environmental impacts observed were considerably less extensive than those observed in high density carp ponds. Of 20 water quality parameters monitored, 10 (50%) had seasonal averages that differed significantly from the control group. However, of those 10 parameters, 9 exhibited deviations from the control ponds which were less severe than those observed in the high density carp treatments (see above). Only dissolved carbons showed particularly large increases relative to the carp treatments, undoubtedly representing leaching during the massive simultaneous death of macrophyte stands. The hallmark of these herbicide impacts is that they are short lived. Macrophyte populations and associated water conditions recover relatively quickly, often so much so as to require several chemical applications during a growing season to maintain control. Fish kills associated with oxygen depletion after the application of herbicides are the most commonly encountered ecological impact of chemical control. Large-scale decomposition results in high oxygen demands for several weeks following application to large plant

Table 20. Cost comparison of 10 years of biological and chemical macrophyte control on a typical 0.44-ha pond. Based on computer simulations of carp feeding and growth and a constant plant productivity of 178 kg dry weight per season.

Treatment	Concentration	Cost
<u>Herbicide</u>		
Potassium endothall	0.3-3.0 ppm	$600-6,000
Diquat	0.5-1.0 ppm	$2,900-5,850
Average		$3,850
<u>Grass carp</u>		
50 g fish	50 kg/ha	$440
200 g fish	60 kg/ha	$396
Average		$418

populations (Gorden et al. 1982; Fig. 15). While acute short-term oxygen depletion is characteristic of herbicide application, it should be noted that herbivorous carp, when stocked in excessive numbers, can have equivalent effects which in fact last for much longer periods of time (Fig. 15).

It is the long-term nature of biological control that makes it attractive economically, and at the same time makes it ecologically more dangerous than chemical control (toxicological issues notwithstanding). Fortunately the degree of ecological disturbance associated with herbivorous fish is not linearly related to stocking density. At low to moderate stocking rates little ecologically significant impact is observed. Overstocking, however, can apparently trigger a series of changes in the basic ecological and physical structure of lentic ecosystems that make the short-term impacts of herbicide application pale in comparison.

RECOMMENDATIONS TO THE DEPARTMENT OF CONSERVATION

On the basis of the studies conducted by the Illinois Natural History Survey and other research organizations over the past 4 years, these recommendations are made to the Illinois Department of Conservation concerning the use of herbivorous carp for plant control in Illinois waters:

Recommendation 1

The hybrid carp and the triploid grass carp should be legalized in Illinois for use as biological control agents against nuisance aquatic macrophyte populations.

Rationale. The grass carp and its derivatives can provide effective and relatively inexpensive control of a wide variety of aquatic plants currently considered to be problematic within Illinois. However, because a remote but real risk of major environmental damage exists if reproducing grass carp populations become permanently established in our major river

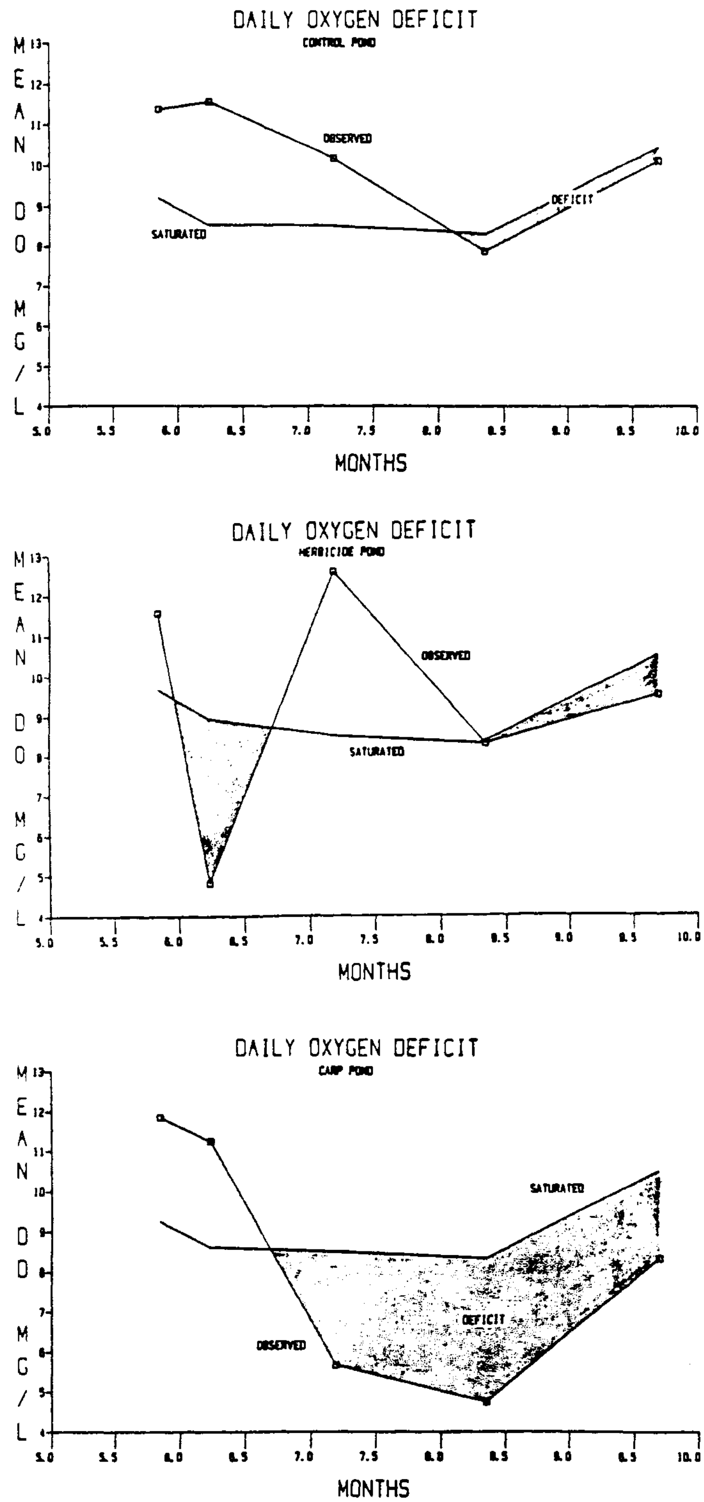


Fig. 15. Daily average oxygen deficit curves for typical control, herbicide treated, and high density carp ponds. Shaded areas represent deficit.

systems, reproductive incompetence should be the primary prerequisite for legalization of any strain or genetic derivative of the white amur. Both the hybrid and the triploid grass carp are, to the best of our current knowledge, likely to be functionally sterile. There is less certainty about the sterility of the triploid grass carp than that of the hybrid, but the triploid is the more capable of the two in terms of control potential. Furthermore, there is a high probability that the triploid grass carp will both be functionally sterile and will develop some or all secondary sexual characteristics. This development might make them useful in diluting whatever "feral" populations of breeding diploid grass carp exist in the Mississippi drainage. In our opinion, the potential economic and ecological advantages outweigh the slight risks of sporadic reproduction, and early legalization of the triploid grass carp, as well as the hybrid carp, is justified and desirable.

Recommendation 2

The reproductive status of the triploid grass carp should be re-evaluated periodically, and its use in Illinois should be curtailed if it is determined that this fish is not functionally sterile.

Rationale. Since the functional sterility of triploid grass carp produced using large-scale production techniques has not been empirically demonstrated, it would be prudent to formally re-evaluate their reproductive status at a future time when fish of normally reproductive age and size have been available for several years. Because of the large commercial interests involved, there will be continued and well publicized monitoring of gonadal development in the oldest triploid year classes (1983 and 1984) of these fish. A simple review of the published data will probably suffice to ensure that the assumption of sterility remains well founded.

Recommendation 3

Adequate steps should be undertaken to ensure that shipments of grass carp legally entering or being produced in Illinois be at least 95% triploid.

Rationale. There is no way to visually distinguish triploid from diploid grass carp; however, ploidy can be determined quickly from small blood samples, either manually using a microscope for small numbers of fish, or automatically using equipment such as a coulter counter for large numbers. Guaranteeing compliance with regulations legalizing triploid grass carp but prohibiting diploid grass carp will require some form of genetic testing prior to release. Possibilities include (but are not limited to): (1) certification of producers and/or dealers, with periodic sampling for quality control; (2) certification of shipments using random sampling; and (3) mandatory inspection and random sampling of fish immediately prior to authorization for stocking (stocking by permit only). Without some form of ploidy verification, the advantages of legalizing the triploid grass carp would be lost and the widespread introduction of normal diploid grass carp in Illinois would be ensured.

Recommendation 4

The Illinois Department of Conservation should oversee and maintain control of the stocking and distribution of both the hybrid carp and triploid grass carp within the state.

Rationale. The use of grass carp to control aquatic plants is an exciting and powerful bio-technology. As we have tried to emphasize in our final report, there is much potential for good and for harm to our aquatic ecosystems. Rational stocking strategies are crucial if the introduction of these fish into a particular body of water is to augment and not detract from the quality of the existing sport fishery. Multiple uncoordinated stockings by private citizens could devastate public waters, with the long-term (3-5 years) maintenance of what we have called the over-grazing syndrome (Part 2: Chapter 3). Because of the chronic impact possible with the misuse of these fish, their potential for environmental damage is more dramatic than the short-term but acute risks associated with herbicides. For this reason, it is important that stocking densities and frequencies be determined by informed and responsible managers. As with the verification of ploidy, there are numerous possible approaches to controlling stocking within the state. One administrative procedure we suggest is stocking by permit only. Requiring a permit has the double advantage of providing an opportunity for input into the stocking plan as well as an opportunity to arrange for ploidy verification.

Recommendation 5

A pilot-project using triploid grass carp for plant control should be undertaken in several large, representative state-managed lakes for continued data collection, public demonstration, and education.

Rationale. Research at the Illinois Natural History Survey during the past 4 years has focused primarily on the feasibility and impact of using herbivorous carp as biological control agents. Good experimental design considerations led us to use a large number of highly replicated but short-term experiments. However, there are several long-term data sets that would be invaluable in refining the basic stocking strategies and recommendations, including data on (1) long-term survivorship of grass carp in heavily grazed (chronically low plant population) waters; (2) long-term responses of plant communities to grazing pressure; and (3) evaluation of predicted long-term impacts on sport fish populations. The latter is particularly of interest in terms of lakes with substantial pelagic zones in which planktivorous shad are an important link in the piscivore food chain. Furthermore, a pilot project could serve as a useful vehicle for educating the public about the potential uses and abuses of these herbivorous fish, as well as a learning exercise for fisheries managers.

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